

Article

Reduction of CO₂ Emissions in Steelmaking by Means of Utilization of Steel Plant Waste Heat to Stabilize Seasonal Cooling Water Temperature

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Abstract: Production of overall CO₂ emissions has exhibited a significant reduction in almost every industry in the last decades. The steelmaking industry is still one of the most significant producers of CO₂ emissions worldwide. The processes and facilities used at steel plants, such as the blast furnace and the electric arc furnace, generate a large amount of waste heat, which can be recovered and meaningfully used. Another way to reduce CO₂ emissions is to reduce the number of low-quality steel products which, due to poor final quality, need to be scrapped. Steel product quality is strongly dependent on the continuous casting process where the molten steel is converted into solid semifinished products such as slabs, blooms, or billets. It was observed that the crack formation can be affected by the water cooling temperature used for spray cooling which varies during the year. Therefore, a proper determination of the cooling water temperature can prevent the occurrence of steel defects. The main idea is based on the utilization of the waste heat inside the steel plant for preheating the cooling water used for spray cooling in the Continuous Casting (CC) process in terms of water temperature stabilization. This approach can improve the quality of steel and contribute to the reduction of greenhouse gas emissions. The results show that, in the case of billet casting, a reduction in the cooling water consumption can be also reached. The presented tools for achieving these goals are based on laboratory experiments and on advanced numerical simulations of the casting process.

Keywords: steelmaking process; quality improvement; waste heat utilization; numerical simulations; optimal control



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1. Introduction

Steel is one of the most essential materials which influences every aspect of our lives, from infrastructure, transport, building structures, to precision tools and instruments. The level of per capita consumption of steel is treated as an important index of the level of socioeconomic development and living standards in a country. On the other hand, the steelmaking industry is one of the most significant producers of CO₂ emissions worldwide. In the last 50 years, the steelmaking industry has reduced its energy consumption by 61% and it is estimated that about 15–20% of that energy consumption can be further reduced [1]. The processes and facilities used at steel plants, such as the blast furnace and the electric arc furnace, generate a large amount of waste heat, which can be recovered and used, for instance in the next steps of steel processing at the plant. Another way to reduce CO₂ emissions is to reduce the number of low-quality steel products that need to be scrapped due to poor final quality. The use of basic oxygen steelmaking and electric arc furnaces transformed the main production processes, making them faster and more energy efficient. In the 1950s, the previous method of ingot casting was replaced by the continuous casting (CC) method, which significantly accelerated and improved steel production [1].

Nowadays, more than 97% of the world's steel is produced by the now well-matured CC technology [2].

1.1. Heat Recovery in Steelmaking

Development in steelmaking has been mainly focused on increasing steel quality, productivity, product variability, and process automatization since the CC method was introduced [3]. There was no significant interest in the reduction of emissions or the waste heat recovery, though the steelmaking industry has a large impact on the overall production of CO₂ emissions, see report [4]. The worldwide community has agreed to hold the increase of the global average temperature below 2 °C with the aim to fit even below 1.5 °C, which requires the reduction of the production of greenhouse gas emissions as soon as possible. This will require a fundamental transformation of energy-intensive industries, including the steel industry. Heat recovery plays an important role in energy saving in the steel production chain [5]. Although industrial waste heat recovery from exhaust and flue gases has increased, the use of radiative heat, which represents a significant share in steelmaking, is still unused. Almost all high temperature facilities, such as the blast furnace, basic oxygen furnace, CC process, hot rolling, etc., involved in the steel industry have a potential for waste thermal energy recovery. Pérez et al. [6] proposed a solution to radiative heat recovery by using a special reflector located directly in the CC machine. Keplinger et al. [7] investigated the use of a heat recovery system which uses the electric arc furnace waste for steam production. Brandt et al. [8] showed an oil-operated heat exchanger within the off-gas of an electric arc furnace. McBrien et al. [9] overviewed a possible heat recovery network for the entire primary steel production supply chain. This paper describes the possibility of direct use of steel plant waste heat for preheating of the cooling water in the CC process [10].

1.2. Continuous Casting Process

The CC process is a predominant way of liquid steel conversion to solid semifinished products in the form of slabs or billets. The CC processes is attributed to more than 97% of the world's steel production [3,10]. The increased local emissions production in the steel industry is most visualized in China. In 1990, China produced only 5% of the world's steel production while, in 2019, China shared more than 53% of world steel production, see Figure 1. The economic crisis in 2008 caused a deep slump of steel production in the EU. Positive economic results have been reached mostly by steel factories which have been focused on special steel production with higher product capabilities [11], such as higher strength grades, steel plates for barrel boilers, steel design for acidic environments, and steel for offshore technologies. However, the production of these special steel grades requires an additional development and research cost. Well-developed countries made large investments in CC installations during the last decade [12]. Penn et al. [3] described the future trends in CC technology. The quality of steel is a frequently discussed topic and some improvements towards quality final products go hand in hand with environmentally friendly approaches, for instance, reducing the cooling water consumption, increasing the speed of casting, optimizing internal logistics, etc. Recently, new concepts appear in the literature, which come from the Industry 4.0, such as Casting 4.0, digital caster, etc. Miśkiewicz and Wolniak [13] showed how the digitization process can be changed based on Industry 4.0 and whether it contributed to an improvement in energy and material efficiency.

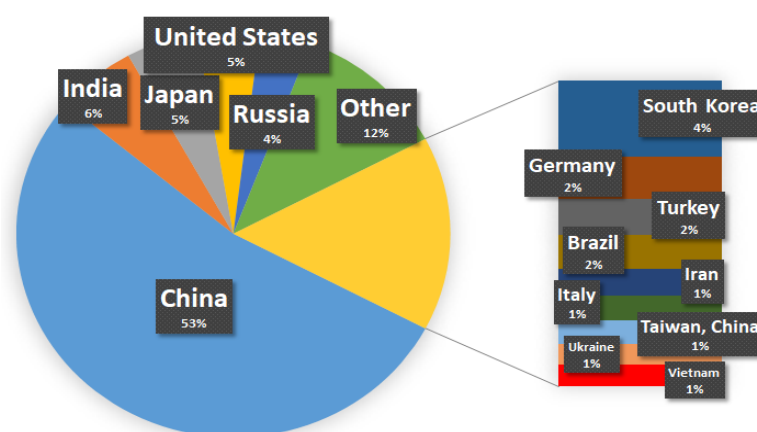


Figure 1. Ratio of the CC process in the world in 2019 [2].

The description of the technology background of steel casting is as follows: the specially treated molten steel of a given chemical composition is transported in a ladle to the CC machine where the molten steel is subsequently poured into the tundish from which the steel is fed through a submerged nozzle into the primary cooling part of a continuous casting machine referred to as a mold, see Figure 2. The growth of the solid shell starts in an internally water-cooled mold (primary cooling zone) [14]. To avoid the destructive scenario of steel breakout, the steel strand must be solidified to a properly calculated thickness to withstand the ferrostatic pressure from the liquid core. The steel is then transported in the secondary cooling zone by rollers and is cooled down by water cooling nozzles. A group of nozzles divides the secondary cooling zone into several cooling loops. In the tertiary cooling zone, the steel surface is cooled down only by free convection and radiation. The molten steel is continuously cooled down from approximately 1550 °C to 800 °C (in the case of billet casting, even temperatures around 400 °C can be reached). A significant factor which has to be considered in the cooling strategy is the solidification phenomenon in terms of latent heat, where a large amount of heat is released, see [15]. More detailed information about CC technology can be found in [10].

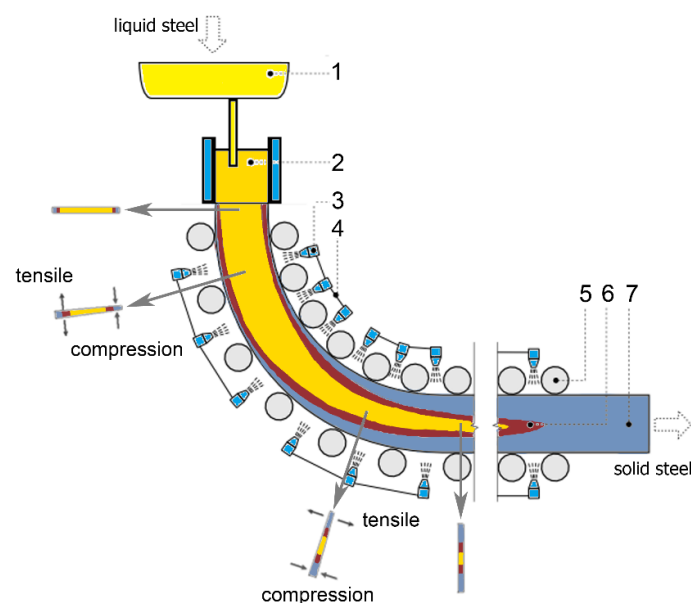


Figure 2. Scheme of the CC process and mechanical stresses during bending and straightening. 1–tundish; 2–mold; 3–nozzle; 4–cooling circuit; 5–roller; 6–solidification point; 7–solid steel [16]. Reused from reference [16].

During the process, the solid shell is permanently subjected to thermal and mechanical tensile/compression stresses and can give rise to crack formation, which leads to poor quality of the products [10]. The occurrence of mechanical stress corresponds to the hot ductility of steel, which varies with the steel temperature. This means that the cooling process has a major influence on its quality, see Jansto [17]. To create a required shell thickness, together with the required mechanical properties of a particular steel grade, strong and intensive cooling has to be applied in the first cooling sections. On the other hand, the subsequent sections are generally set to softer cooling to reach a proper temperature in specific locations, for instance, at the unbending point where increased mechanical stress is applied. During the casting, about 60% of the heat is withdrawn by means of water cooling nozzles, see Klimes et al. [18]. The importance of optimal control of cooling intensity is obvious and investigated in many research papers. In an extensive review published by Doctor et al. [19], 25 optimization approaches are discussed. In general, the cooling intensity is the only parameter that is optimized, for instance, as a function of the casting speed, chemical composition of steel, overheating temperature, etc. However, these research works do not consider the water cooling temperature as one of the parameters, which influences the final steel quality. From the statistically evaluated historical data from steelmakers, it was found out that the temperature of cooling water used for spray cooling also has an influence on steel quality. The steel quality difference between winter and summer seasons is statistically attributed to the temperature difference of cooling water, which changes during the year from approximately 5 °C to 40 °C.

1.3. Simulation Models

The increase of computer power and cloud computing in recent decades allowed the creation of so-called digital twins as a digital representation of real physical systems [20]. These systems integrate the IoT, artificial intelligence, machine learning, and software analytics that serve as decision making support systems. From the physical point of view, a CC is a complex transient heat and mass transfer problem encompassing the phase change by means of the solidification of steel [21]. Digital twins of the CC process are generally based on the complex numerical heat and mass transfer simulation modes. The pioneer works described 1D heat transfer models, such as Meng and Thomas [22]. Alizadeh et al. [23] proposed a 2D model and observed that the casting speed is the most effective parameter for mold heat removal, which means that it is the most important factor in the control of the solidified shell thickness and strand temperature. One of the first 3D solidification models was introduced by Tieu and Kim [24]. Many of these works were far from use in the real casting process, because of the computer power limitations. Today, fully 3D transient numerical models with real boundary conditions are able to run and control the real casting process [25].

In many cases, the numerical models are supplemented by optimization and/or control algorithms. Previous works dealing with optimal control of CC processes were optimized by mathematical programming or heuristic methods. Santos et al. [26] applied the genetic algorithm; Zhemping et al. [27] verified the usage of the ant colony algorithm; Zheng et al. [28] attempted to use the swarm optimization; Mauder et al. [29] applied the firefly algorithm; etc. Combination of the numerical model and the optimal control algorithm creates digital twins which can directly control the real casting process, store and process the casting data, make decisions, and support the process operators [13].

1.4. Aim of the Paper and Applied Methods

This article addresses two basic ideas related to the use of waste heat inside a steel plant for preheating the cooling water used in the CC process. There is an assumption that the temperature of the cooling water affects the final quality of the steel, as is indicated by statistical data from steel mills. The first idea is that the waste heat can be used for so-called cooling water temperature stabilization, which can minimize steel defects and improve the overall quality of steel. The second idea is that the required heat withdrawal in the CC

process can be achieved by different water flows with different cooling water temperatures. Theoretically, it would be possible to minimize the amount of water used for cooling by controlling its temperature and making the casting process more environmentally friendly.

Confirmation of these assumptions by using industrial experiments is too expensive, time-consuming, and, in some particular cases, impossible. This paper uses a combination of the results of experimental laboratory measurements and an advanced numerical solidification model. The numerical model has already been validated by several real casting processes. The experimental measurement was provided by Heat Transfer and Fluid Flow Laboratory at Brno University of Technology. The laboratory is focused on experimental research for academic and industrial projects dealing mainly with spray cooling and heat transfer since 1994 [30].

2. Methods

2.1. Modelling of Continuous Casting Process

In this study, the original 3D numerical model of the temperature field, the so-called Brno Dynamic Solidification Model[®], is used [25]. The BrDSM has a long-term history, and its current and previous versions have been successfully applied in several steel plants over the world. During the years of development, this model was gradually improved and refined, based on data from the industry, such as pyrometer measurements, temperature scanner measurements, the radioisotopic method for the measurement of solidification point, etc. The BrDSM can be easily adapted to any geometry of a CC machine, and it can be used for slab, billet, and thin slab casting. The BrDSM also supports massive parallel computing on graphics processing units (GPUs) for high-speed on-line calculations. All outputs are collected and stored in the server database for subsequent statistical evaluation. The advanced optimal control algorithm based on fuzzy logic (FL-BrDSM) has become an integral part of the model. The FL regulator adjusts the input parameters such as the casting speed or cooling intensity in the secondary cooling zone based on actual surface temperatures. The combination of the FL regulator with the GPU model allows the prediction of future temperature behavior of the strand, and it works as a model predictive control system. The detailed description of the BrDSM and FL regulator is described in Mauder et al. [31] and a description of the FL regulator applied to CC can be found in Mauder et al. [16].

The results of the BrDSM strongly depend on the boundary conditions. The boundary conditions include the meniscus temperature, heat flux in the mold and under the rollers, forced convection under the nozzles, and free convection and radiation in the tertiary cooling zone. In the literature, a large number of empirical relationships, to determine boundary conditions through the CC machine, can be found [14,32]. However, these empirical formulas include many constants and parameters and their correct determination for a particular cooling setup is difficult. Proper determination of boundary conditions is crucial in the case of obtaining an accurate result, see Ramirez et al. [33]. The more accurate method is to use the operating temperature measurement. In the mold, the cooling intensity is calculated from the energy balance equation while considering the thickness of the mold walls and the water temperature difference between the entry and exit of the cooling channels. The real data comes directly from the measurement of cooling water temperature and flow rates, which are affected by the casting speed and steel carbon content. In the secondary cooling zone, the strand is mainly cooled by the water or water–air mixture nozzles. The cooling efficiencies of cooling nozzles are affected by parameters such as air and water flow, nozzle position, and impact angles. The domain between two supporting rollers can be divided into four different cooling regions: (1) roller contact area, (2) pre-nozzle and water pool area, (3) spraying area, and (4) post-nozzle area, see Figure 3.

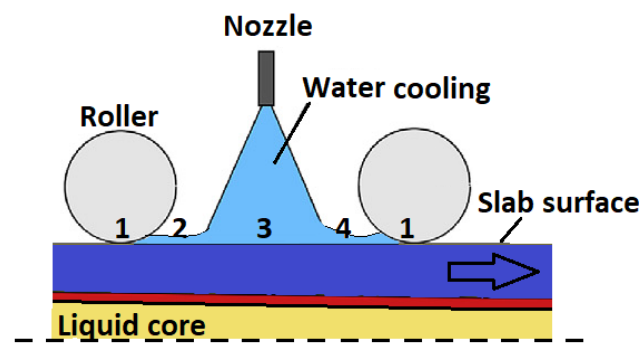


Figure 3. Heat transfer mechanism under the nozzle.

The heat withdrawal in the pre-nozzle (2) and post-nozzle (4) areas involves mainly free convection and radiation. In the spraying area (3), where the spray of water or water-air mixture cools the strand surface, the forced convection plays an important role. Nozzle parameters like air and water flow, nozzle position, air pressure, and impact angle affect the cooling efficiency. The question that needs to be answered is whether the cooling efficiency is also influenced by the cooling water temperature. The boundary condition beneath the spray nozzle can be expressed as:

$$-k \frac{\partial T}{\partial x} \Big|_{x=0} = HTC(T - T_{water}) + \sigma \epsilon (T^4 - T_{water}^4), \quad (1)$$

where T is the temperature [K]; k is the thermal conductivity [$\text{Wm}^{-1}\text{K}^{-1}$]; T_{water} is the cooling water temperature [K]; x is the space dimension [m]; HTC is the heat transfer coefficient beneath the nozzle [$\text{Wm}^{-2}\text{K}^{-1}$]; σ is the Stefan-Boltzmann constant [$\text{Wm}^{-2}\text{K}^{-4}$]; ϵ is the emissivity of the slab surface [-]. The heat flux extracted from the surface can be expressed as a product of the heat transfer coefficient and a difference between the surface temperature and the coolant temperature. The estimation of HTC values can be made by several empirical formulas such as those in Ha et al. [34]. The main disadvantage of the use of empirical formulas is generally based on many constants and parameters, and their usage is limited to the particular nozzle type and nozzle position. The effect of cooling water temperature is not included in these formulas. The model discussed in this paper uses the HTC distribution from experimental measurements of the spraying characteristics of all nozzles from a so-called hot plate laboratory instrument.

2.2. Experimental Setup and HTC Measurement

The cooling water temperature at the steel plants generally changes during the year within a range from 5 °C to 40 °C. This range of cooling water temperature can theoretically influence the cooling characteristics of the nozzles typically used in the CC process and hence influence the final quality of steel. There is an assumption that the HTC is also a function of cooling water temperature.

The dependence of the HTC on the surface temperature is well known. The so-called Leidenfrost temperature is the temperature which is the interface between the high intensity and low intensity of cooling [35,36]. Raudensky et al. [37] conducted the HTC measurements on 7 mm thin carbon plates made of austenitic steel integrating 16 thermocouples. One half of the thermocouples was positioned 1 mm under the surface. The second half was welded directly to the surface. A major part of the laboratory configuration is an electric furnace used for the initial heating of the plate. The test plate was heated to the initial temperature of approximately 1200 °C, and then positioned under a nozzle. The computer control driving linear mechanism moved the spraying nozzle under the plate with a pneumatically driven deflector. The deflector was closed on the way back to its initial position. This simulates the slab movement in the real CC process. For these experiments, small air-mist nozzles, which are usually deployed for the cooling of slab in CC process, were also used. The experiments were conducted with different water

temperatures, which increased by 10 °C from 20 °C to 80 °C. The HTC was then obtained from the measured temperatures by the solution of the inverse heat conduction problem, see Pohanka [38]. The experiment and schematic of the laboratory configuration can be seen in Figure 4.

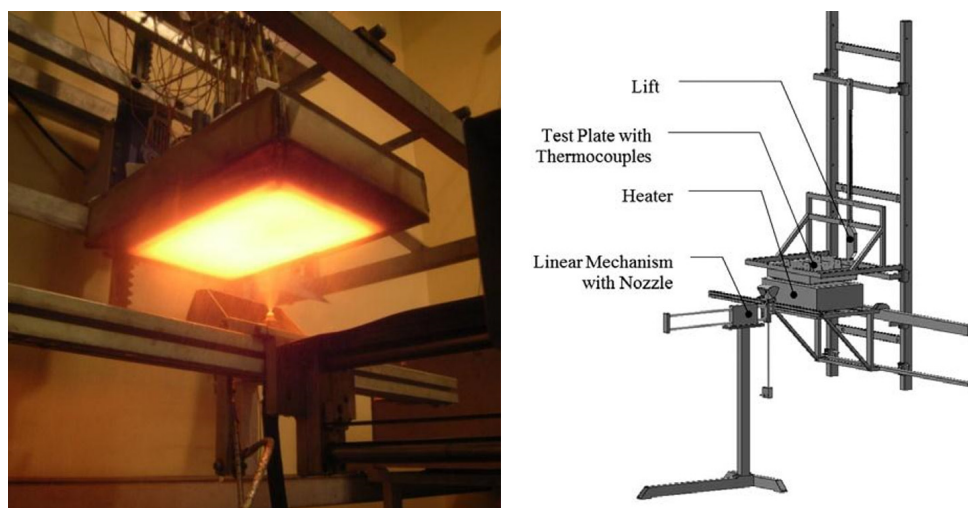


Figure 4. Left—the test plate sprayed by a nozzle, right—basic parts of the experimental laboratory configuration. Reprinted with permission from ref. [38].

The experiment results show a substantial dependence of the spray cooling efficiency on the cooling water temperature, see Hnizdil et al. [39]. The results shown in Figure 5 are the averaged values of the HTC in the impacting area (from −150 mm to +150 mm in the longitudinal and transversal directions). The results demonstrate a significant shift in the Leidenfrost temperature. Changing the water temperature from 20 °C to 80 °C causes a shift in the Leidenfrost temperature by 130 °C to lower temperatures. The HTC values are almost the same for all experiments, but in the high temperature area (Figure 6) it is possible to see that the HTC increased with the increased coolant temperature. The difference of HTC is about $30 \text{ W m}^{-2} \text{ K}^{-1}$ and provides higher cooling intensity above the Leidenfrost temperature while using warmer water. This result can be explained by the positive effect between the water temperature and the boiling point that allows a faster setting of the boiling regime with high heat transfer rates.

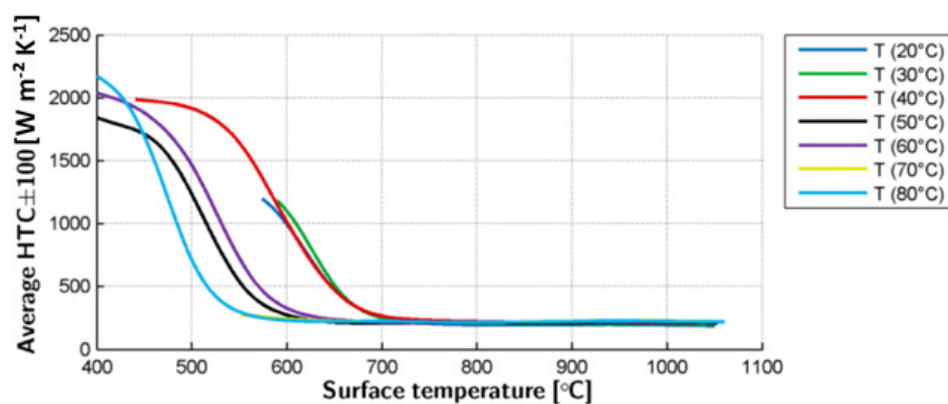


Figure 5. The influence of cooling water temperature on HTC [39].

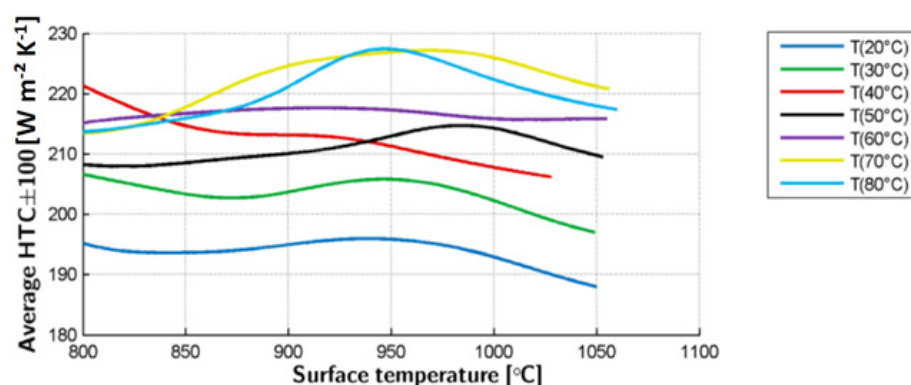


Figure 6. HTC in high temperature area [39].

3. Results and Discussion

The average HTC from the experiments (Figures 5 and 6) were imported to the boundary conditions database in BrDSM. The temperature of cooling water is one of the parameters which can be set at the beginning of the simulation. For comparison, both the billet and the slab casting are investigated. In the first area of billet casting, hard cooling is applied and the surface temperatures of the steel fall below the structural changes of the steel (approximately 500–600 °C). This process has a positive effect on the quality of billets. On the other hand, in slab casting, a smooth decrease in surface temperature leads to a higher quality of the slab [16]. To obtain more general comparison results, the geometries of both casters for slab or billet casting were supposed to have the same dimension in the casting direction. Thus, both casters are 20 m long with the secondary cooling zone divided into six independent regulation loops. This simplification does not affect the principle of the casting process. The cross section of the billet is 0.12×0.12 m and the cross section of the slab is 1.50×0.25 m.

The numerical results are influenced by the thermophysical properties of the cast steel used in the computation. For the test case, the common stainless steel grade 304 was selected [40]. The thermophysical parameters of the steel used in the presented numerical experiment are listed in Table 1.

Table 1. The thermophysical properties of the steel used in this study [40].

	Specific Heat Capacity	Thermal Conductivity	Density
Liquid steel	780 J/kgK	22 W/mK	6900 kg/m ³
Solid steel	700 J/kgK	22 W/mK	7200 kg/m ³
Liquidus temperature	1453 °C		
Solidus temperature	1396 °C		
Latent heat	247 kJ/kgK		

The results of BrDSM are depicted in the form of the temperature curves at specific points (core, top surface, bottom surface, corner, etc.) from the meniscus to the end of the CC machine (in this case 20 m). Four different water cooling temperatures (WCT) were simulated: 20 °C, 40 °C, 60 °C, and 80 °C, to see the difference in the temperature distribution. For comparison, other casting parameters such as the casting speed (1.5 m/min for billet and 0.5 m/min for slab casting), cooling water flow rates, superheat temperature, etc. were kept constant. In Figure 7, the BrDSM results for billet casting where the solidification region between solidus and liquidus temperatures (mushy zone) and cooling zones (mold, secondary and tertiary cooling zone) can be seen. The results of the BrDSM for the slab casting process are visualized in Figure 8.

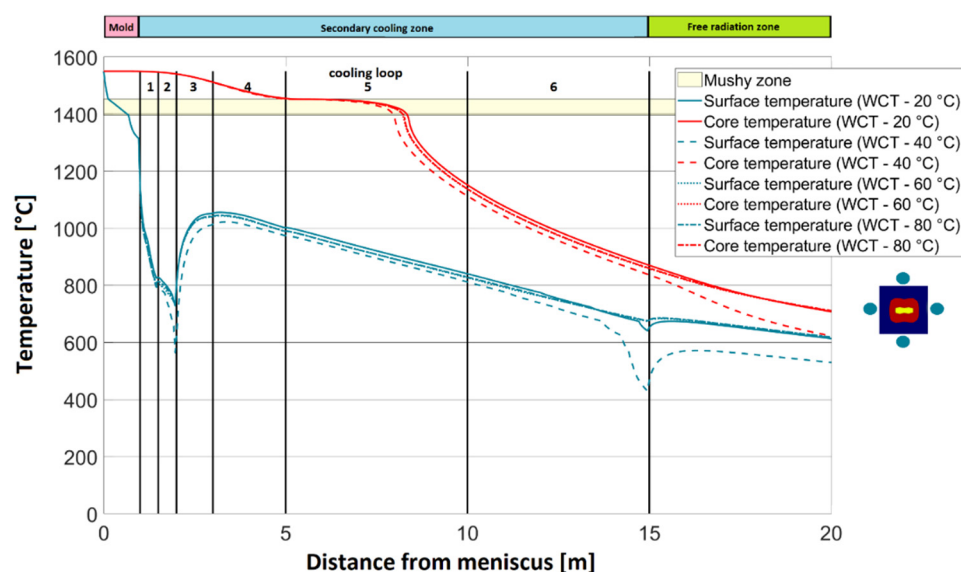


Figure 7. Results of BrDSM simulation for billet caster geometry.

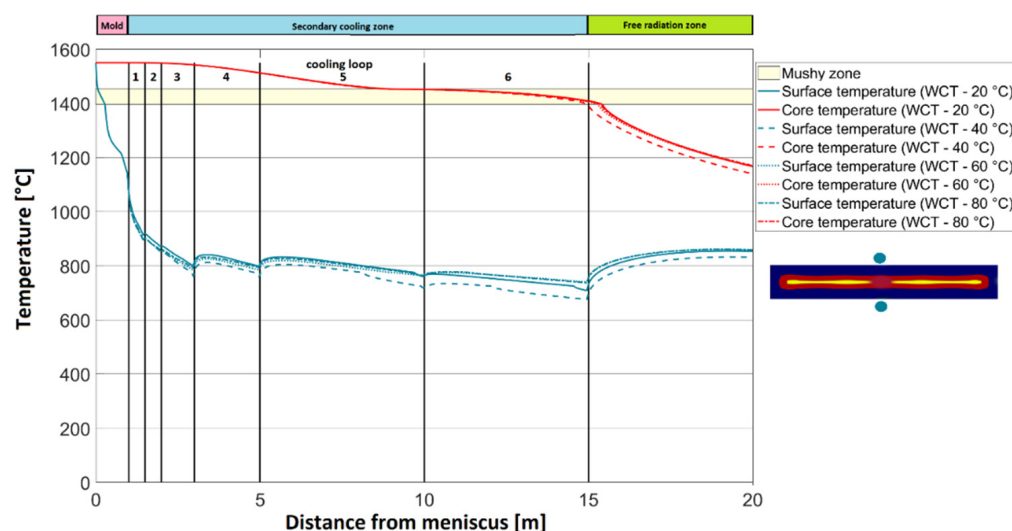


Figure 8. Results of BrDSM simulation for slab caster geometry.

From the results, it can be seen that the steel surface temperatures are influenced by the cooling water temperature. The paper assumption about the temperature distribution difference while using different cooling water temperatures is thus confirmed.

The difference in temperature distribution between the billet and slab casting process is visible. The higher cooling intensity exhibited 40 °C water, which has higher HTC below surface temperature of 840 °C, see Figure 8. The surface temperatures in billet casting are influenced more by different cooling water temperatures than in the case of slab casting. This is caused by the Leidenfrost effect, which is not presented in the slab casting process, because during the slab casting process the surface temperatures did not reach the region under the Leidenfrost temperature approx. 700 °C (Figure 5). On the other hand, in billet casting, the Leidenfrost effect is presented for 40 °C water, see the first cooling loops in Figure 7. The cooling water of 40 °C exhibited similar HTC as 60 °C and 80 °C water in the high surface temperature region and also had an advantage over the 20 °C and 30 °C water where the Leidenfrost temperature was positioned to the higher surface temperatures.

At first sight, temperature profiles in slab casting may look similar, but it must be emphasized that even a small temperature deviation from the optimal surface temperature can cause surface cracks and defects [16]. Therefore, the first idea of water temperature

stabilization during the whole year is a right approach towards a higher quality of continuously cast steel. The use of waste heat recovery towards temperature stabilization which was carried out in this work meets the ecological framework that the metallurgical industry should follow.

The same findings can be applied to the case of billet casting. The simulation of billet casting with the cooling water temperature of 40 °C has significantly larger heat withdrawal due to the Leidenfrost effect. This fact leads to the second idea of this article regarding to the minimization of cooling water consumed during the casting. To achieve the same cooling intensity for a cooling water temperature of 20 °C and a cooling water temperature of 40 °C, it is necessary to reduce the flow of cooling water to a temperature of 40 °C. This calculation has provided in total 6.3% of water savings for billet casting with a 40 °C cooling water temperature. Due to the great amount of water used in billet casting, these savings are not negligible.

To estimate the value of the heat flux which is required to preheat the cooling water, the general heat balance equation can be used:

$$\dot{Q} = (1 - \gamma)^{-1} \cdot \dot{m}_{water} \cdot c_{water} \cdot (T_{required} - T_{water}), \quad (2)$$

where \dot{Q} is the rate of heat flow [W]; γ is the coefficient of energy conversion losses [0,1]; \dot{m}_{water} is the mass flow rate [kg s^{-1}]; c_{water} is the average specific heat of water [$\text{J kg}^{-1}\text{K}^{-1}$] between inlet water temperature and the optimal/required temperature.

For the test case, the required temperature was set to 40 °C and the BrDSM found the optimal mass flow rate of cooling water to be 16.78 kg s^{-1} . In the case that the temperature of inlet water is only 10 °C and the estimation of energy loss during the energy conversation is 25%, the rate of heat flow according to Equation (2) is 1406.4 kW. In the case of the special heat capture reflector proposed by Pérez et al. [6], the Tunnel Shaped reflector can capture $32,700 \text{ Wm}^{-2}$ (assuming the reflector temperature is 500 °C) of radiative heat from the slab. The examined slab dimensions were set to $1.50 \text{ m} \times 0.25 \text{ m}$, which means that Tunnel Shaped reflectors must cover the slab in the longitudinal direction at least in 43 m. Due to the size of the steelmaking plant, this distance can be acceptable for most of the CC machines. Moreover, if these reflectors will be placed directly behind the CC machine, then the recovery waste heat does not need any long and loss-making transportation and can directly preheat the cooling water.

4. Conclusions

The heat transfer and solidification model of continuous steel casting (BrDSM) was originally designed and used as a tool to reach optimal casting conditions, which ensure both high-quality steel products as well as increased productivity. Increasing quality of steel products decreases the number of rejected and scrapped slabs/billets and, eventually, the production of CO₂ emissions. It is assumed that 38% of steel defects are related to the incorrect process parameter values, see [41]. This paper shows another possibility of how the final quality of steel products can be increased by using BrDSM and experimental measurements of HTC. The problem of maintaining high production quality through the year due to different cooling water inlet temperatures can be solved by using steel plant waste heat for preheating cooling water. The proposed approach has two main benefits:

- Cooling water stabilization throughout the seasons, which also stabilizes the surface slab/billet temperatures and can preserve high steel quality (for billet and slab casting).
- By using the BrDSM, the optimal water cooling temperature can be found in the sense of minimizing cooling water consumption (for billet casting).

The experiments supported with computer simulations showed that the temperature of cooling water influences the steel temperature distribution during the casting process and should be taken as one of the parameters which influence the final steel quality. This confirms the assumption that there is an effect of the cooling water temperature on the quality of steel products, which resulted from the statistical evaluation of production data

from the steel plant. In this paper, the pioneer study was presented and the possibility for improvement of CC technology in an ecological way was shown. The future concerns in this field are focused on more HTC experiments and the collection of extensive HTC data for different cooling nozzle types and to run BrDSM simulation for a particular billet/slab casting process with pyrometric verification of the real process.

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